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Indian Standard

METHODS OF TEST FOR
VOLUME AND SURFACE RESISTIVITY OF
SOLID ELECTRICAL INSULATING MATERIALS

(First Revision)

UDC 621·315·611 : 621·317·72

INDIAN STANDARDS INSTITUTION
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

Indian Standard

METHODS OF TEST FOR
VOLUME AND SURFACE RESISTIVITY OF
SOLID ELECTRICAL INSULATING MATERIALS

(*First Revision*)

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Indian Standard

METHODS OF TEST FOR VOLUME AND SURFACE RESISTIVITY OF SOLID ELECTRICAL INSULATING MATERIALS

(*First Revision*)

0. FOREWORD

0.1 This Indian Standard (First Revision) was adopted by the Indian Standards Institution on 30 October 1979, after the draft finalized by the Electrical Insulation Sectional Committee had been approved by the Electrotechnical Division Council.

0.2 This standard was first issued in 1966. This revision has been necessitated to take into account the recent developments in the methods of measurement of volume and surface resistivity. As such it has been aligned with its international counterpart. For the values of resistivity greater than 10^{10} Ω-m, certain additional requirements in the geometry and shape of the electrodes is needed. The same has been accounted for in this revision.

0.3 In the preparation of this standard, assistance has been derived from IEC Document 15A (Central Office) 35 Draft revision of publication 93 : Methods of test for volume and surface resistivity of solid electrical insulating materials, issued by the International Electrotechnical Commission (IEC).

0.4 In reporting the result of a test made in accordance with this standard, if the final value, observed or calculated, is to be rounded off, it shall be done in accordance with IS : 2-1960*.

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1. SCOPE

1.1 These methods of test cover procedures for the determination of volume and surface resistance and calculations for determination of volume and surface resistivity of solid insulating materials.

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*Rules for rounding off numerical values (*revised*).

1.2 Both volume and surface resistance tests are affected by the following factors: (a) the magnitude and time of voltage application, (b) the nature and geometry of the electrodes, and (c) the temperature and humidity of the ambient atmosphere during conditioning and measurement. Recommendations are made for these factors.

2. TERMINOLOGY

2.0 For the purpose of this standard, the following definitions shall apply.

2.1 Volume Resistance — The quotient of a direct voltage applied between two electrodes in contact with a specimen, and the steady state current between the electrodes, excluding current along the surface, and neglecting possible polarization phenomena at the electrodes.

> NOTE — The volume resistance generally depends on the time of electrification. Unless otherwise specified this time is taken as one minute.

2.2 Volume Resistivity — The quotient of a dc electric field strength and the steady state current density within an insulating material. In practice it is taken as the volume resistance reduced to a cubical unit volume.

> NOTE — The SI unit of volume resistivity is Ω-m. In practice the unit Ω-cm is also used.

2.3 Surface Resistance — The quotient of a direct voltage applied between two electrodes on a surface of a specimen, and the current between the electrodes at a given time of electrification, neglecting possible polarization phenomena at the electrodes.

> NOTE 1 — Unless otherwise specified the surface resistance is determined after one minute of electrification.

> NOTE 2 — The current mainly passes through a surface layer of the specimen and any associated moisture and surface contaminant, but also includes a component through the volume of the specimen.

2.4 Surface Resistivity — The quotient of a dc electric field strength, and the linear current density in a surface layer of an insulating material. In practice it is taken as the surface resistance reduced to a square area. The size of the square is immaterial.

> NOTE — The SI unit of surface resistivity is Ω-m. In practice this is sometimes referred to as 'ohm per square'.

2.5 Electrodes — Measuring electrodes are conductors of defined shape, size and configuration in contact with the specimen being measured.

> NOTE — Insulation resistance is the quotient of a direct voltage applied between two electrodes in contact with a specimen and the total current between the electrodes. The insulation resistance depends on both volume and surface resistivity of the specimen. (*see* IS : 2259-1963*).

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*Methods of test for determination of insulation resistance of solid insulating materials.

3. SIGNIFICANCE

3.1 Insulating materials are used in general to isolate components of an electrical system from each other and from earth; solid insulating materials may also provide mechanical support. For these purposes it is generally desirable to have the insulation resistance as high as possible, consistent with acceptable mechanical, chemical and heat-resisting properties. Surface resistance changes very rapidly with humidity, while volume resistance changes only slowly, although the final change may be greater.

3.2 Volume resistivity can be used as an aid in designing an insulator for a specific application. The change of resistivity with temperature and humidity may be great and must be known when designing for operating conditions. Volume resistivity measurements are often used in checking the uniformity of an insulating material, either with regard to processing or to detect conductive impurities that affect the quality of the material and that may not be readily detectable by other means.

3.3 When a direct voltage is applied between electrodes in contact with a specimen, the current through it decreases asymptotically towards a steady state value. The decrease of current with time may be due to dielectric polarization and the sweep of mobile ions to the electrodes. For materials having volume resistivities less than about 10^{10} Ω-m (10^{12} Ω-cm) the steady state is in general reached within one minute, and this time is used as the electrification time. For materials of higher volume resistivity the current may continue to decrease for several minutes, hours, days, or even weeks. For such materials therefore longer electrification times are used, and if relevant, the material is characterized by the time dependence of the volume resistivity.

3.4 Surface resistance or conductance cannot be measured accurately, only approximated, because more or less volume conductance is nearly always involved in the measurement. The measured value is largely a property of the contamination of the surface of the specimen at the time of measurement. However, the permitivity of the specimen influences the deposition of contaminants, and their conductive capabilities are affected by the surface characteristics of the specimen. Thus surface resistivity is not a material property in the usual sense, but can be considered to be related to material properties when contamination is involved.

3.4.1 With homogeneous materials the measurement of surface resistivity of a clean surface without contamination or humidity will give results which do not differ from what could be deduced from determinations of the volume resistivity. Some materials, such as laminates, may have quite different resistivities in a surface layer and in the interior. It may therefore be of interest to measure the intrinsic property of a clean

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surface. Cleaning procedures aimed at producing consistent results should be fully specified bearing in mind the possible effect of solvents or procedures on the surface.

3.4.2 The surface resistance, especially when high, often changes in an erratic manner, and in general depends strongly on the time of electrification; for measurements, one minute of electrification is usually specified.

4. POWER SUPPLY

4.1 A source of very steady direct voltage is required. This may be either by batteries or a rectified and stabilized power supply. The degree of stability required is such that the change in current due to any change in voltage is negligible compared with the current to be measured.

4.2 Commonly specified test voltages to be applied to the complete specimens are 85, 100, 250, 500, 1 000, 2 500, 5 000, 10 000 and 15 000 V. Of these the most frequently used are 100, 500 and 1 000 V.

4.3 In some cases the specimen resistance depends upon the polarity of the applied voltage.

4.4 If the resistance is polarity dependent, this should be reported. The geometric (logarithmic) mean of the two resistance values is taken as the result.

4.5 Since the specimen resistance may be voltage dependent, the test voltage should be reported.

5. MEASURING METHODS AND ACCURACY

5.1 Methods — The methods commonly in use for measuring high resistances are either direct methods or comparison methods.

5.1.1 The direct methods depend upon simultaneous measurement of the direct voltage applied to the unknown resistance and the current through it (voltmeter-ammeter method).

5.1.2 The comparison methods establish the ratio of the unknown resistance to the resistance of a known resistor, either in a bridge curcuit, or by comparison of currents through the resistances at fixed voltage.

5.1.3 Examples illustrating the principles are described in Appendix A.

5.1.4 The voltmeter-ammeter method requires a reasonably accurate voltmeter, but the sensitivity and accuracy of the method depend mainly on the properties of the current-measuring device, which may be a galvanometer, an electronic amplifier instrument, or an electrometer.

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5.1.5 The bridge method requires only a sensitive current detector as measuring instrument, and the accuracy is mainly determined by the known bridge arm resistors, which are obtainable with high precision and stability over a wide range of resistance values.

5.1.6 The accuracy of the current comparison method depends on the accuracy of the known resistor, and on the stability and linearity of the current-measuring device, including associated measuring resistors, etc, whereas the exact values of current are insignificant, as long as the voltage is constant.

5.1.7 Determination of volume resistivity in accordance with **10.1** using a galvanometer in the voltmeter-ammeter method is feasible for resistances up to about 10^{11} Ω, for higher values the use of a dc amplifier or electrometer is recommended.

5.1.8 In the bridge method it is not possible to measure the current directly in the short-circuited specimen (*see* **10.1**).

5.1.9 The methods utilizing current-measuring devices permit automatic recording of the current to facilitate determination of the steady state (*see* **10.1**).

5.1.10 Special circuits and instruments for measuring high resistance are available. These may be used, provided that they are sufficiently accurate and stable, and that where needed they enable the specimen to be properly short circuited, and the current measured before electrification.

5.2 Accuracy — The measuring device should be capable of determining the unknown resistance with an overall accuracy of at least ± 10 percent for resistances below 10^{10} Ω, and ± 20 percent for higher values. See also Appendix A.

5.3 Guarding

5.3.1 The insulation of the measuring circuit is composed of materials which, at best, have properties comparable with those of the material under test. Errors in the measurement of the specimen may arise from:

    a) Stray current from spurious external voltages which are usually unknown in magnitude and often sporadic in character.

    b) Undue shunting of the specimen resistance, reference resistors, or the current-measuring device by insulation, having resistance of unknown, and possibly variable magnitude.

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5.3.2 An approximate correction of these difficulties may be obtained by making the insulation resistance of all parts of the circuit as high .as possible under the conditions of use. This may lead to unwieldy apparatus which is still inadequate for measurement of insulation resistances higher than a few hundred megohms. A more satisfactory correction is obtained by using the technique of guarding.

5.3.3 To ensure satisfactory operation of the equipment a measurement should be made with the high potential lead to the specimen disconnected. Under this condition, the equipment should indicate infinite resistance within its sensitivity. If suitable standards of known values are available, they may be used to test the operation of the equipment.

5.3.4 Guarding depends on interposing, in all critical insulated parts, guard conductors which intercept all stray currents that might otherwise cause errors. The guard conductors are connected together, constituting the guard system and forming with measuring terminals a three-terminal network. When suitable connections are made, stray currents from spurious external voltages are shunted away from the measuring circuit by the guard system, the insulation resistance from either measuring terminal to the guard system shunts a circuit element which should be of very much lower resistance, and the specimen resistance constitutes the only direct path between the measuring terminals. By this technique the probability of error is considerably reduced. Figure 1 shows the basic connections for guarded electrodes used for volume and suface resistance measurements.
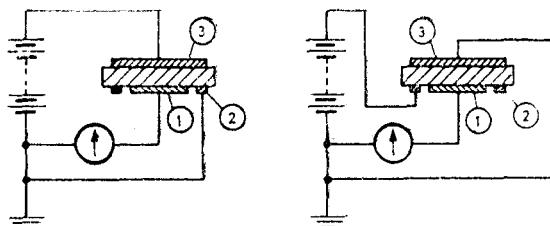

1A   Volume Resistivity   1B   Surface Resistivity

Fig. 1   Basic Connections for Guarded Electrodes

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5.3.5 Proper use of the guard system for the method involving current measurement is illustrated in Fig. 2 and 4, where the guard system is shown connected to the junction of the voltage source and current measuring device. In Fig. 3, for the Wheatstone bridge method, the guard system is shown connected to the junction of the two lower-valued resistance arms. In all cases, to be effective, guarding must be complete, and must include any control operated by the observer in making the measurement.
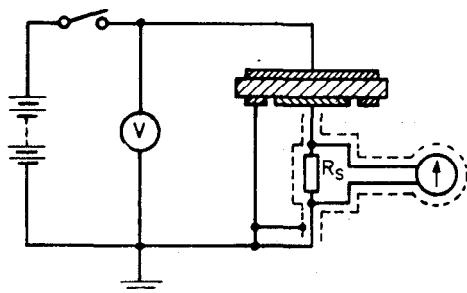
FIG. 2   VOLTMETER-AMPEREMETER METHOD USED FOR
MEASURING VOLUME RESISTANCE
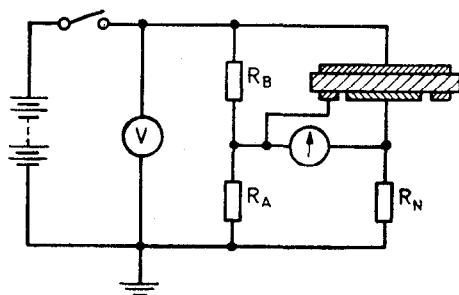
FIG. 3   WHEATSTONE BRIDGE METHOD USED FOR
MEASURING VOLUME RESISTANCE

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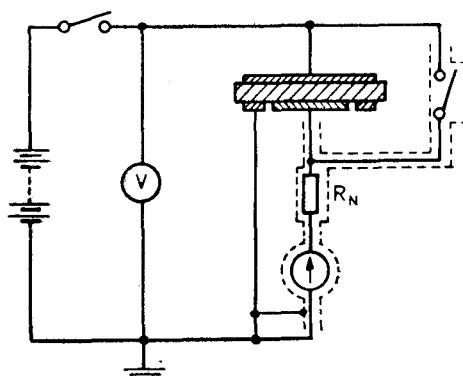
Fig. 4   Ammeter Method used for Measuring
Volume Resistance

5.3.6 Errors in current measurements may result from the fact that the current-measuring device is shunted by the resistance between the guarded terminal and the guard system. This resistance should be at least ten and preferably one hundred times that of the current-measuring device. In some bridge techniques, the guard and measuring terminal are brought to nearly the same potential but a standard resistor in the bridge is shunted by the resistance between the unguarded terminal and the guard system. This resistance should be at least ten and preferably one hundred times that of the reference resistor.

5.3.7 Electrolytic, contact, or thermal emf existing between guard and guarded terminals can be compensated if they are small. Care must be taken that such emf do not introduce appreciable errors in the measurements.

6. TEST SPECIMENS

6.1 Volume Resistance

6.1.1 For the measurement of volume resistance the test specimen may have any practicable form that allows the use of a third electrode to guard against error from surface effect. For specimens that have negligible surface leakage, the guard may be omitted when measuring volume resistance provided that it has been shown that its omission has negligible effect on the result.

6.1.2 The gap on the surface of the specimen between the guarded and guard electrodes should be of uniform width and as narrow as possible

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provided that the surface leakage does not cause error in the measurement. A gap of 1 mm is usually the smallest practicable.

6.1.3 The average thickness of the specimen is determined in accordance with the relevant specification, the measuring points being distributed uniformly over the area to be covered by the measuring (guarded) electrode.

6.1.4 Examples of electrode arrangements with three electrodes are shown in Fig. 5 (circular electrodes on a flat specimen) and Fig. 6 (cylindrical electrodes on a tubular specimen). In the measurement of volume resistance electrode No. 1 is the guarded electrode, electrode No. 2 is the guard electrode, and electrode No. 3 is the unguarded electrode. The diameter d_1 (Fig. 5), or length l_1 (Fig. 6) of the guarded electrode should be at least ten times the specimen thickness, δ, and for practical reasons usually at least 25 mm. The diameter d_4 (or length l_4) of the unguarded electrode, and the outer diameter d_3 of the guard electrode (or length l_3 between the outer edges of the guard electrodes) should be equal to the inner diameter d_2 of the guard electrode (or length l_2 between the inner edges of the guard electrodes) plus at least twice the specimen thickness.
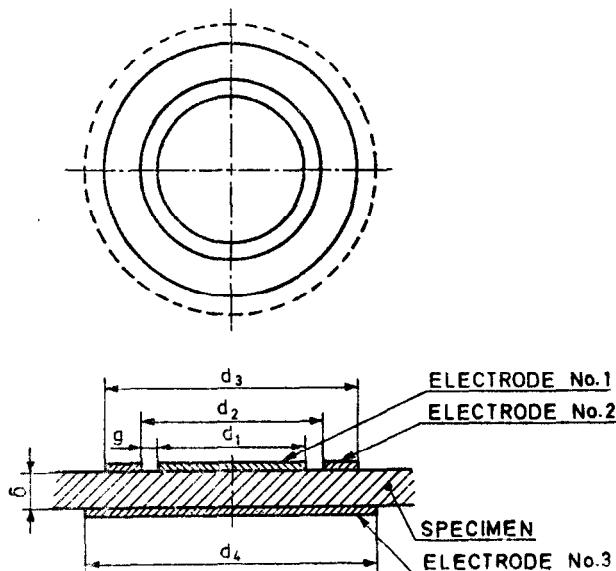

FIG. 5 EXAMPLE OF ELECTRODE ARRANGEMENT ON
FLAT SPECIMEN

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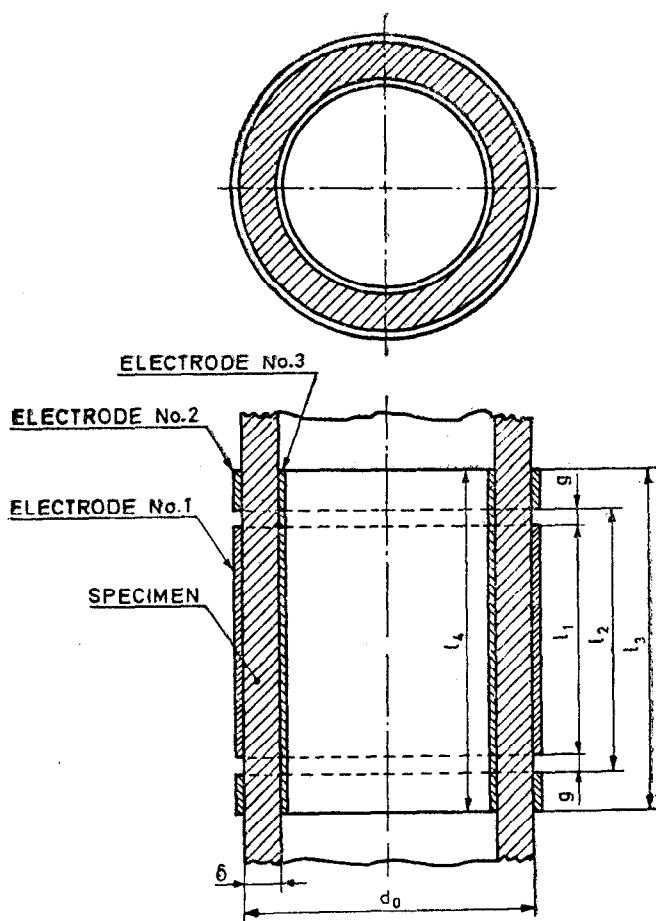
FIG. 6   EXAMPLE OF ELECTRODE ARRANGEMENT ON
TUBULAR SPECIMEN

6.2 Surface Resistance — For the measurement of surface resistance
the test specimen may have any practicable form that allows the use of a
third electrode to guard against error from volume effects.   The three-
electrode arrangements of Fig. 5 and 6 are recommended.   The resistace
of the surface gap between electrode No. 1 and 2 is measured directly
by using electrode No. 1 as the guarded electrode, electrode No. 3 as

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the guard electrode and electrode No. 2 as the unguarded electrode. The resistance so measured includes the surface resistance between electrode No. 1 and 2 and the volume resistance between the same two electrodes. With suitable dimensioning of the electrodes, however, the effect of that volume resistance can be made negligible for wide ranges of ambient conditions and material properties. This condition may be achieved for the arrangement of Fig. 5 and 6 when the electrodes are dimensioned so that the surface gap width, g, is at least twice the specimen thickness; 1 mm is normally the smallest practicable. The diameter d_1 (or length l_1) of the guarded electrode should be at least ten times the specimen thickness δ, and for practical reasons usually at least 25 mm.

6.2.1 Alternatively, straight electrodes or other arrangements with suitable dimensions may be used.

NOTE — For comparative measurements of surface resistance it is recommended to use the arrangement of Fig. 5 with $d_1 = 50$ mm, $d_2 = 60$ mm, $d_3 = 80$ mm.

7. ELECTRODE MATERIAL

7.1 General — The electrodes for insulating materials should be of a material that is readily applied, allows intimate contact with the specimen surface and introduces no appreciable error because of electrode resistance or contamination of the specimen. The electrode material should be corrosion resistant under the conditions of the test. The following are typical electrode materials that may be used. The electrodes must be used with suitable backing plates of the given form and dimensions.

It may be advantageous to use two different electrode materials or methods of application to see if appreciable error is introduced.

7.2 Conductive Silver Paint — Certain types of commercially available, high-conductivity silver paints, either air-drying or low-temperature baking varieties are sufficiently porous to permit diffusion of moisture through them and thereby allow the test specimens to be conditioned after application of the electrodes. This is a particularly useful feature in studying resistance-humidity effects as well as changes with temperature. However, before conductive paint is used as an electrode material, it should be established that the solvent in the paint does not affect the electrical properties of the specimen. Reasonably smooth edges of guard electrodes may be obtained with a fine-bristle brush. However, for circular electrodes, sharper edges may be obtained by the use of a compass and silver paint for drawing the outline circles of the electrodes and filling in the enclosed areas by brush. Clamp-on masks may be used if the electrode paint is sprayed on.

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7.3 Sprayed Metal — Sprayed metal may be used if satisfactory adhesion to the test specimen can be obtained. Thin sprayed electrodes may have certain advantages in that they are ready for use as soon as applied. They may be sufficiently porous to allow the specimen to be conditioned, but this should be verified. Clamp-on masks may be used to produce a gap between the guarded and the guard electrodes.

7.4 Evaporated or Sputtered Metal — Evaporated or sputtered metal may be used under the same conditions as given in **7.3** where it can be shown that the material is not affected by ion bombardment or vacuum treatment.

7.5 Liquid Metal Electrodes — Liquid metal electrodes may be used and give satisfactory results. The metal forming the upper electrode should be confined by stainless steel rings, each of which should have its lower rim reduced to a sharp edge by bevelling on the side away from the liquid metal. Fig. 7 shows the electrode arrangement. Mercury is not recommended for continuous use or at elevated temperatures due to toxic effects.

7.6 Colloidal Graphite — Colloidal graphite, dispersed in water or other suitable medium, may be used under the same conditions as given in **7.2**.

7.7 Conducting Rubber — Conducting rubber may be used as an electrode material, and it has the advantages that it can be applied and removed from the specimen quickly and easily. As the electrodes are applied only during the time of measurement, they do not interfere with the conditioning of the specimen. The conducting rubber material must be soft enough to ensure that effective contact to the specimen is obtained when a reasonable pressure is applied.
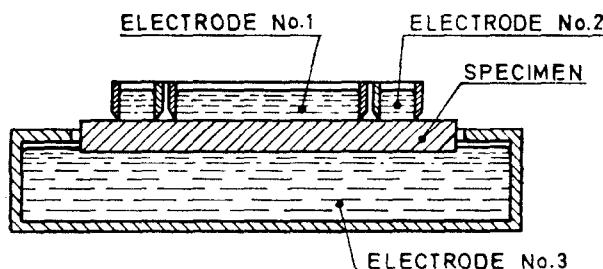
FIG. 7 ARRANGEMENT OF LIQUID ELECTRODES

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7.8 Metal Foil

7.8.1 Metal foil may be applied to specimen surfaces as electrodes for volume resistance measurement, but they are not suitable for surface resistance measurement. Lead, antimonial lead, aluminium, and tin foils are in common use and are usually attached to the specimen by a minimum quantity of petrolatum, silicone grease, oil or other suitable material, as an adhesive. A pharmaceutically obtainable jelly of the following composition is suitable as a conductive adhesive:

Anhydrous polyethylene glycol of molecular weight 600	800 parts by mass
Water	200 parts by mass
Soft soap (pharmaceutical quality)	1 part by mass
Potassium chloride	10 parts by mass

7.8.2 The electrodes shall be applied under a smoothing pressure sufficient to eliminate all wrinkles and to work excess adhesive towards the edge of the foil where it can be wiped off with a cleansing tissue. Rubbing with a soft material such as the finger has been used successfully. This technique can be used satisfactorily only on specimens that have very smooth surfaces. With care the adhesive film can be reduced to 0·002 5 mm or less.

8. SPECIMEN MOUNTING

8.1 In mounting specimens for measurement, it is important that there shall be no conductive paths between the electrodes or between the measuring electrodes and earth that will have a significant effect on the reading of the measuring instrument. That part of the surface of a specimen which is to be measured shall not be touched by anything other than an untouched surface of another specimen of the same material. When surface resistance is to be measured, the surface shall not be cleaned unless agreed or specified.

9. CONDITIONING

9.1 The conditioning that a specimen should receive depends upon the material being tested and should be specified in the material specification.

Recommended conditions are given in IS : 2260-1973* and the relative humidities associated with various salt solutions are given in IS : 8145-1976†. Mechanical vapourization systems may be used.

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*Specification for preconditioning, conditioning and testing of solid electrical insulating materials (*first revision*).

†Specification for test chambers of non-injection type for constant relative humidity.

Both volume and surface resistivities are particularly sensitive to temperature changes. The change is exponential. It is therefore necessary to measure the volume and surface resistance of the specimen while under specified conditions. Extended periods of conditioning are required to determine the effect of humidity on volume resistivity since the absorption of water into the body of the dielectric is a relatively slow process. Water absorption usually decreases volume resistance. Some specimens may require months to reach equilibrium.

10. TEST PROCEDURE

10.0 Specimens prepared in accordance with **6, 7, 8** and **9** are used in the following procedures.

10.1 Volume Resistivity

10.1.1 Measure the specimen thickness, the dimensions of the electrodes, and the width of the surface gap (g), with the required accuracy.

10.1.2 Before measurement the specimen must be brought into a dielectrically stable condition. To obtain this, short circuit the measuring electrode No. 1 and 3 of the specimen (Fig. 1A) through the measuring device and observe the changing short circuit current, while increasing the sensitivity of the current-measuring device as required. Continue until the short circuit current attains a fairly constant value, small compared with the expected steady state value of the current under electrification, or if relevant, the current at 100 min of electrification. As there is a possibility of a change in the direction of the short circuit current, the short circuit should be maintained even if the current passes zero. The magnitude and direction of the short circuit current I_0 are noted when it becomes essentially constant, which may require several hours.

10.1.3 Then apply the specified direct voltage and start a timing device simultaneously. Unless otherwise specified, measure the current after the following times of electrification: 1, 2, 5, 10, 50, 100 minutes. If two successive readings of the current are the same, the test may be terminated, and the current thus found used to calculate the volume resistivity. The electrification time until the first of the identical measurement is recorded. If the steady state is not reached within 100 minutes, the volume resistivity is reported as a function of electrification time.

10.2 Surface Resistivity

10.2.1 Measure the dimensions of the electrodes and the width of the surface gap (g), with the required accuracy.

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10.2.2 Apply the specified direct voltage, and determine the resistance between the measuring electrodes on the specimen surface (electrode No. 1 and 2, Fig. 1B). The resistance shall be determined after one minute of electrification, even though the current has not necessarily reached a steady state value within this time.

11. CALCULATION

11.1 Volume Resistivity

11.1.1 The volume resistivity shall be calculated from the following formula:

$$P = R_x A / \delta$$

where

P = volume resistivity in Ω-m,

R_x = volume resistance in Ω measured as specified in **10.1**,

A = effective area of the guarded electrode in m², and

δ = average thickness of the specimen in m.

11.1.2 Formulae for calculating the effective area A for some particular electrode arrangements are given in **A-3**.

11.1.3 For some materials with high resistivity, particularly when they are in the form of thin films, the short circuit current I_0 prior to electrification (*see* **10.1**) may not be negligible compared to the steady state current I_s during electrification. In such cases the volume resistance is determined as:

$$R_x = U_x / (I_s \pm I_0)$$

where

R_x = volume resistance in Ω,

U_x = applied voltage in V,

I_s = steady state current in A during electrification, and

I_0 = short circuit current in A prior to electrification.

The minus sign is used when I_0 is in the same directions as I_s, otherwise the plus sign is used.

11.2 Surface Resistivity — The surface resistivity shall be calculated from the following formula:

$$P_s = R_x p / g$$

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where

P_s = surface resistivity in Ω,

R_x = surface resistance in Ω measured as specified in **10.2.**

p = effective perimeter in m of the guarded electrode for the particular electrode arrangement employed, and

g = distance in m between the electrodes.

11.3 Reproducibility — Because of the variability of the resistance of a given specimen with test conditions, and because of non-uniformity of the same material from specimen to specimen, determinations are usually not reproducible to closer than ± 10 percent and are often even more widely divergent (a range of values of 10 to 1 may be obtained under apparently identical conditions).

11.3.1 In order that measurements on similar specimens are to be comparable, they must be made with approximately equal voltage gradients.

12. REPORT

12.1 The report shall include at least the following:

a) Description and identification of the material (name, grade, colour, manufacturer, etc);

b) Shape and dimensions of the specimen;

c) Type and dimensions of the electrodes and guards;

d) Conditioning of the specimen (cleaning, pre-drying, conditioning time, humidity and temperature, etc);

e) Test conditions (specimen temperature, relative humidity);

f) Method of measurement;

g) Applied voltage;

h) Volume resistivity (when relevant);

Where specimens reach a steady state in the same electrification time, give the individual results, and report the central value as the volume resistivity. Where some specimens do not reach the steady state in this electrification time, report the number failing to do so and give the results on them separately. Where results are dependent on electrification time, report this relationship; and

j) Surface resistivity (when relevant).

Give the individual values after one minute of electrification, and report the central value as the surface resistivity.

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APPENDIX A

(*Clauses* 5.1.3 *and* 5.2)

EXAMPLES OF MEASURING METHODS AND THEIR ACCURACY

A-1. VOLTMETER-AMMETER METHOD

A-1.1 This direct method employs the circuit shown in Fig. 2. The applied voltage is measured by the dc voltmeter. The current is measured by a current-measuring device, which may be a galvanometer (now seldom used), an electronic amplifier instrument, or an electrometer.

A-1.2 The galvanometer should have high current sensitivity and be provided with a universal shunt (also known as Ayrton shunt). It should be short circuited while the specimen is being charged to avoid damage to it during this period. The unknown resistance in Ω is calculated as:

$$R_x = U/k\alpha,$$

where

U = applied voltage in V,

k = sensitivity of the shunted galvanometer in ampere per scale division, and

α = deflection in scale divisions.

A-1.3 Resistances up to about 10^{10} to 10^{11} Ω can be measured at 100 V with the required accuracy by means of a galvanometer.

A-1.4 An electronic amplifier instrument or an electrometer with high input resistance shunted by a resistor of known high resistance, R_s may be used as current-measuring device. The current is measured in terms of a voltage drop U_s across R_s. The unknown resistance, R_x, is calculated as:

$$R_x = R_s \, U_x/U_s$$

where

U_x = applied voltage (provided $R_s \ll R_x$)

A-1.5 A number of different resistors R_s may be included in the instrument case, and the instrument is then often graduated directly in ampere or submultiples thereof.

A-1.6 Here also the maximum resistance that can be measured with the required accuracy depends on the properties of the current-measuring device. The error in U_s is determined by the indicator error, the

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amplifier zero drift and gain stability. In adequately designed amplifiers and electrometers the instability in gain is negligible, and the zero drift can be held so low that it is of no concern in relation to the times involved in these measurements. The indicator error for high gain electronic voltmeters is typically ± 2 to 5 percent of full-scale deflection, and resistors up to 10^{12} Ω known with about the same degree of accuracy are feasible. If the voltage-measuring device has an input resistance greater than 10^{14} Ω, and full-scale deflection at an input voltage of 10 mV, a current of 10^{-14A} can be measured with an accuracy of about ± 10 percent.

A-1.7 A resistance of 10^{16} Ω can thus be measured at 100 V with the required accuracy by means of a precision resistor with very high resistance and an electronic amplifier voltmeter or electrometer.

A-2. COMPARISON METHODS

A-2.1 Wheatstone Bridge Method — The test specimen is connected in one arm of a Wheatstone bridge as shown in Fig. 3. The three known arms shall be of as high resistance as practicable, limited by the errors inherent in such resistors. Usually the resistance R_B is changed in decade steps and the resistance R_A is used for fine balance adjustment, and R_X is fixed for the duration of measurement. The detector shall be a dc amplifier, with an input resistance high compared to any of these arms. The unknown resistance, R_X is calculated as follows:

$$R_x = R_N\, R_B/R_A$$

where R_A, R_B and R_N are as shown in Fig. 3.

A-2.1.1 The maximum percentage error in the computed resistance is the sum of the percentage errors in R_A, R_B and R_N, when the null detector has adequate sensitivity. If R_A and R_B are wire-wound resistors with values below, for example, 1 MΩ, their errors can be made negligible, and for measuring very high resistances, R_N could be, for instance, 10^9Ω, which may be known with an accuracy of ± 2 percent. The accuracy with which the ratio R_B/R_A can be determined depends essentially on the sensitivity of the null detector. If the unknown resistance $R_X \gg R_N$, the uncertainty $\triangle r$ in determination of the ratio $r = R_B/R_A$ is determined by $\triangle r/r = I_g R_X/U$, where I_g is the minimum perceivable null detector current and U the voltage applied to the bridge. If, for example, an electronic amplifier instrument with input resistance 1 MΩ and full-scale deflection for an input voltage of 10^{-5} V is used, the lowest perceivable current will be about 2×10^{-13A} corresponding to 2 percent of full-scale deflection. With this value of I_g, $U = 100$ V, and $R_x = 10^{13}$ Ω one gets $\triangle r/r = 0.02$ or 2 percent.

A-2.1.2 Resistances up to 10^{13} to 10^{14} Ω can thus be measured at 100 V with the required accuracy by the Wheatstone bridge method.

A-2.2 Ammeter Method

A-2.2.1 This method employs the circuit shown in Fig. 4, and the components are the same as those described in **A-1** with the addition of a resistor R_N of known value, and a switch to short circuit the unknown resistance. It is very important that the resistance of this switch in the open position is much higher than the unknown resistance R_x in order not to affect the measurement of the latter. This is most easily obtained by short circuiting R_x with a copper wire, which is removed when measuring R_x. In general it is preferable to leave R_N in the circuit at all times to limit the current in case of failure of the specimen in order to protect the the current-measuring device.

A-2.2.2 With the switch open the current through R_x and R_N is determined as specified in **10** by noting the instrument deflection α_x and the shunt ratio F_x, the shunt being adjusted to give as near as possible maximum scale deflection. Thereafter R_x is short circuited and the current through R_N determined by noting the instrument deflection α_N and the shunt ratio F_N, the shunt again being adjusted to give as near as possible maximum scale deflection, starting from the least sensitivity. Provided the applied voltage U does not change during the measurement, R_x can be calculated from:

$$R_x = R_N(\alpha_N F_N/\alpha_x F_x - 1)$$

If $\alpha_N F_N/\alpha_x F_x > 100$, the approximated formula $R_x = R_N \alpha_N F_N/\alpha_x F_x$ may be used.

A-2.2.3 This method allows R_x to be determined with about the same accuracy as by the direct method described in **A-1** but has the advantage that the current-measuring device is checked *in situ* by the measurement of R_N, the error of which can be made negligible by using a wire-wound resistor, which is readily obtainable with an accuracy of $0·1$ percent or better. The measurement of the current through R_x may thus be more reliable.

A-3. FORMULAE FOR CALCULATING A AND p

A 3.1 For most purposes the following approximate formulae are sufficiently accurate for calculating the effective area A and the effective perimeter p of the guarded electrode.

A-3.1.1 *The Effective Area A*

    a) Circular electrodes (Fig. 5) $A = \pi (d_1 + g)^{2}/4$

    b) Rectangular electrodes $A = (a + g) (b + g)$

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     c) Square electrodes $\qquad A = (a + g)^2$

     d) Tubular electrodes (Fig. 6) $\qquad A = \pi (d_0 - \varepsilon) (l_1 + g)$

where d_0, d_1, g, and l_1 are the dimensions indicated in Fig. 5 and 6, and a and b are length and width respectively of the guarded electrode when rectangular or square. The dimensions are expressed in metres, and A in square metres.

A-3.1.2 *The Effective Perimeter*

     a) Circular electrodes (Fig. 5) $\qquad p = \pi (d_1 + g)$

     b) Rectangular electrodes $\qquad p = 2 (a + b + 2g)$

     c) Square electrodes $\qquad p = 4 (a + b)$

     d) Tubular electrodes $\qquad p = 2 \pi d_0$

where the meaning of the symbols is the same as in **A-3.1.1**.

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3202-1965	Code of practice for climate proofing of electrical equipment
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4819-1968	Thin vulcanized fibre sheet (including leatheroid) for electrical purposes
4820-1968	Vulcanized fibre sheets for electrical purposes
5596-1970	Method of test for determining deleterious substances in fibrous insulating materials
5711-1970	Vulcanized fibre rods and tubes for electrical purposes
6103-1971	Method of test for specific resistance (resistivity) of electrical insulating liquids
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6792-1972	Method for determination of electric strength of insulating oils
6855-1973	Method of sampling for liquid dielectrics
7084-1973	Bitumen based filling compounds for electrical purposes
7571-1974	Methods of tests for ceramics for telecommunication and allied purposes
7755-1975	High tension insulating cotton tape impregnated with bitumen based compounds
7809 (Part I)-1975	Pressure sensitive adhesive tapes for electrical purposes: Part I General requirements
7809 (Part II)-1977	Pressure sensitive adhesive tapes for electrical purposes: Part II Methods of test
7809 (Part III/Sec 1)-1977	Pressure sensitive adhesive tapes for electrical purposes: Part III Specifications for individual materials, Section 1 Plasticized polyvinylchloride tapes with non-thermosetting adhesive
7809 (Part III/Sec 4)-1977	Pressure sensitive adhesive tapes for electrical purposes: Part III Specifications for individual materials, Section 4 Cellulosic paper creped with thermosetting adhesive
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8264-1976	Air drying anti-tracking insulating varnishes for electrical purposes
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8516-1977	Methods of test for determining electrolytic corrosion with insulating materials
8570-1977	Presspaper for electrical purposes

INTERNATIONAL SYSTEM OF UNITS (SI UNITS)

Base Units

Quantity	Unit	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

Supplementary Units

Quantity	Unit	Symbol
Plane angle	radian	rad
Solid angle	steradian	sr

Derived Units

Quantity	Unit	Symbol	Definition
Force	newton	N	$1\ N = 1\ kg.m/s^2$
Energy	joule	J	$1\ J = 1\ N.m$
Power	watt	W	$1\ W = 1\ J/s$
Flux	weber	Wb	$1\ Wb = 1\ V.s$
Flux density	tesla	T	$1\ T = 1\ Wb/m^2$
Frequency	hertz	H	$1\ H = 1\ c/s\ (s^{-1})$
Electric conductance	siemens	S	$1\ S = 1\ A/V$
Electromotive force	volt	V	$1\ V = 1\ W/A$
Pressure, stress	pascal	Pa	$1\ Pa = 1\ N/m^2$

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